Land perspective on surface energy budget

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The interdisciplinary evolution of land models

The interdisciplinary evolution of land models

Land as a lower boundary to the atmosphere → **Land as an integral component of the Earth System**

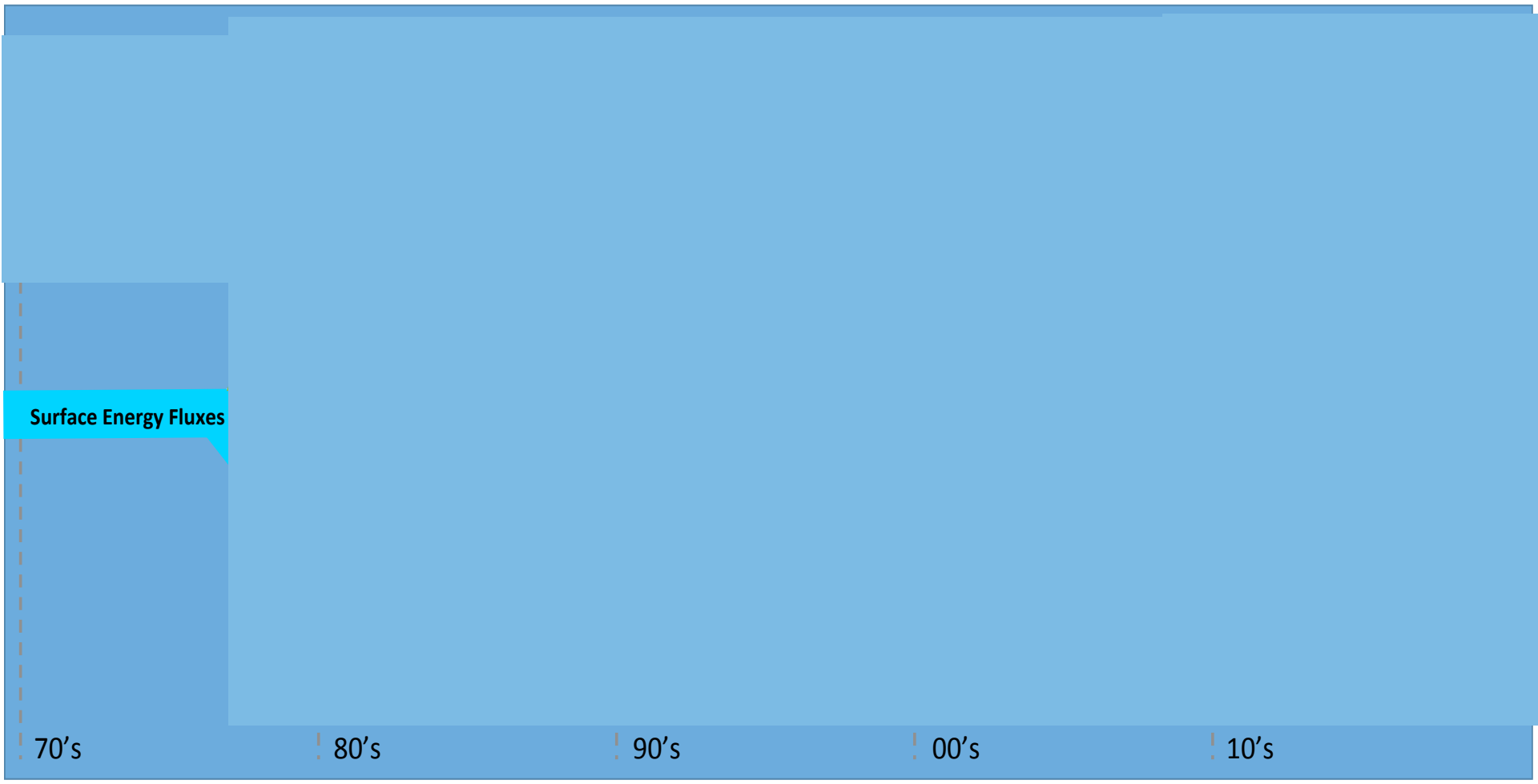
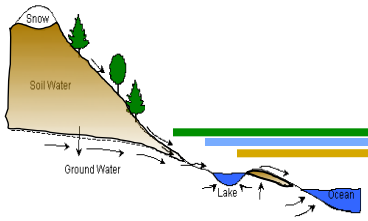
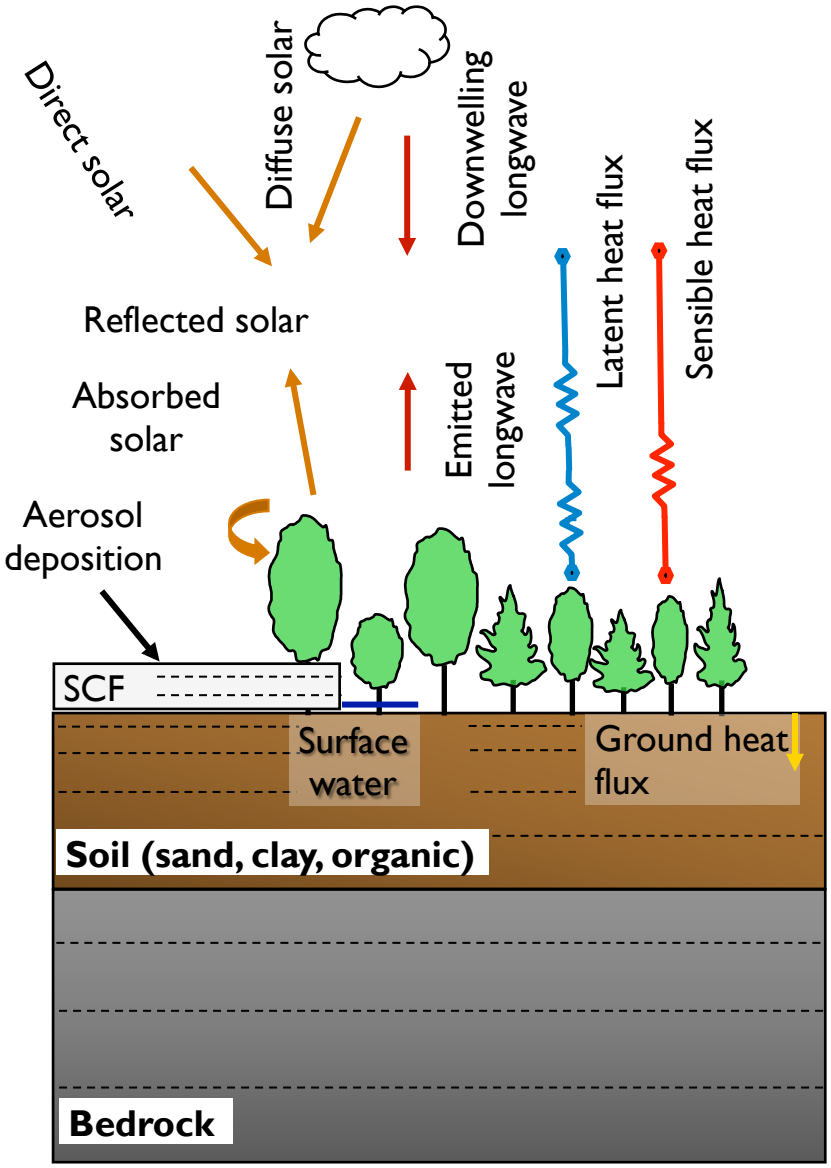


Figure: Fisher, Lawrence, Bonan, Clark, unpublished

Surface Energy Balance





$$S^{\uparrow} - S^{\downarrow} + L^{\uparrow} - L^{\downarrow} = \lambda E + H + G$$

$S^{\uparrow}$, $S^{\downarrow}$ are down(up)welling solar radiation,

$L^{\uparrow}$, $L^{\downarrow}$ are up(down)welling longwave rad,

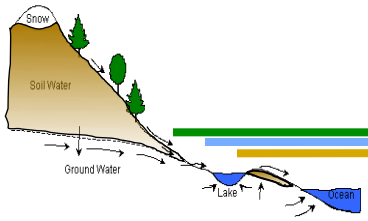
λ is latent heat of vaporization,

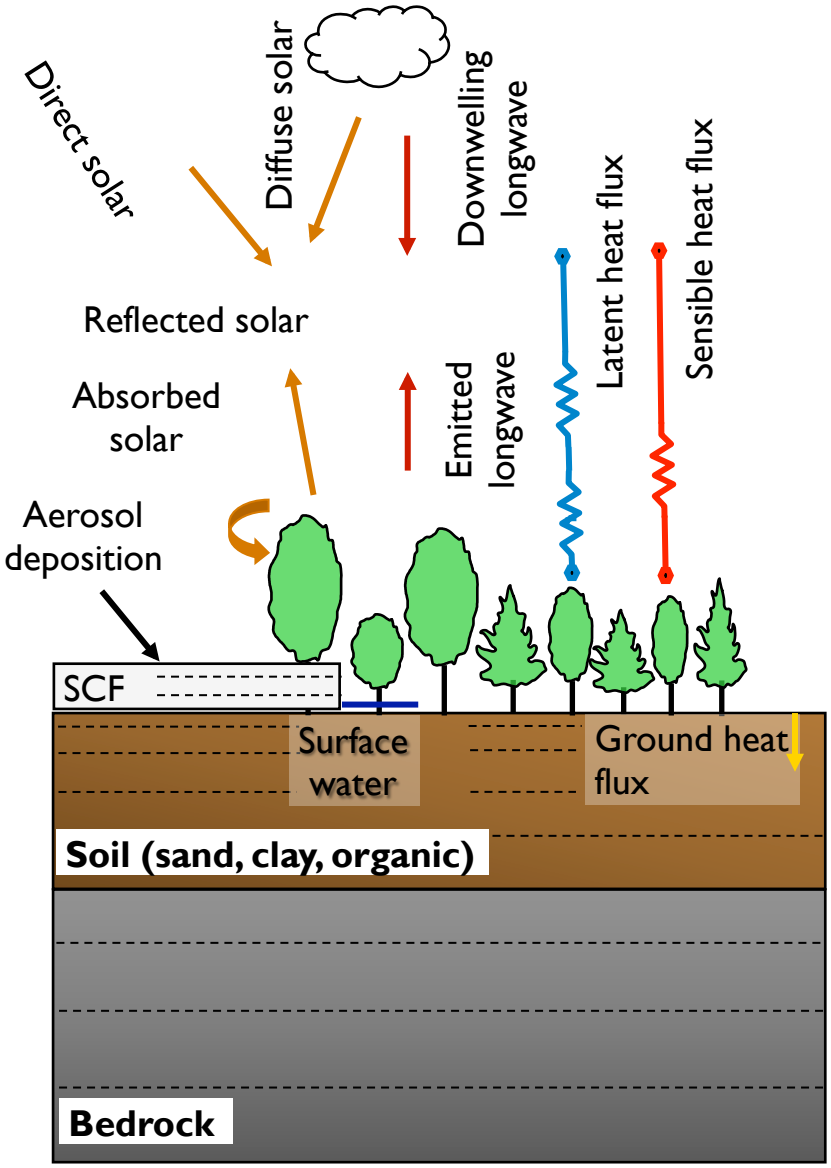
E is evaporation,

H is sensible heat flux

G is ground heat flux

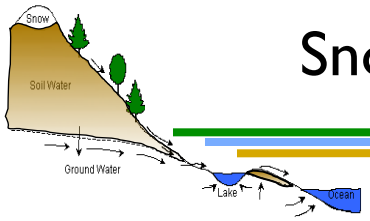
Surface Energy Balance





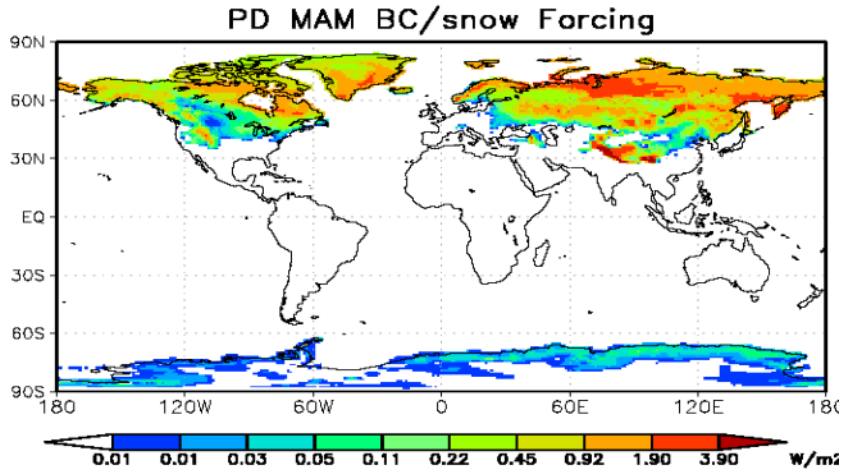
Surface albedo a function of

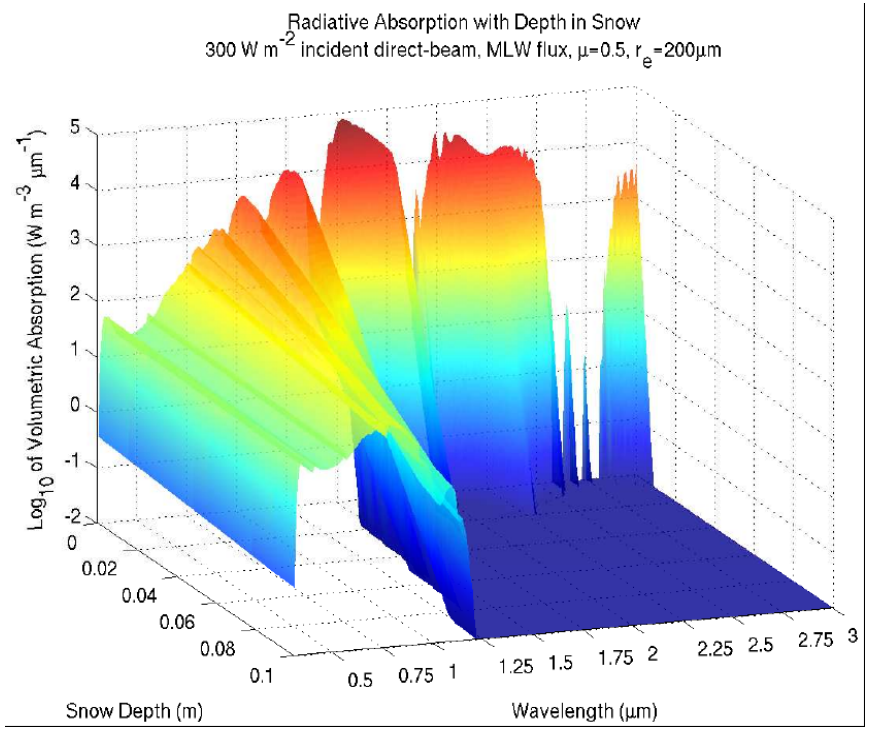
- Land type (vegetated, glacier, lake, urban)
- Plant functional type (leaf and stem reflectance and transmission, leaf angle)
- Snow albedo
  - Snow cover fraction
  - Snow age (snow grain size)
  - Snow darkening due to aerosols (SNICAR)
  - Vertical absorption of solar
- Soil color and soil moisture
- Solar zenith angle
- Amount of direct vs diffuse solar radiation
- Amount of visible vs IR solar radiation



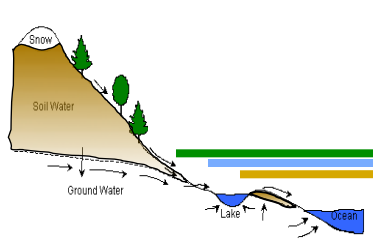
Snow, Ice, and Aerosol Radiative Model (SNICAR)

- Snow darkening from deposited black carbon, mineral dust, and organic matter
- Vertically-resolved solar heating in the snowpack
- Snow aging (evolution of effective grain size) based on:
  - Snow temperature and temperature gradient
  - Snow density
  - Liquid water content and
  - Melt/freeze cycling



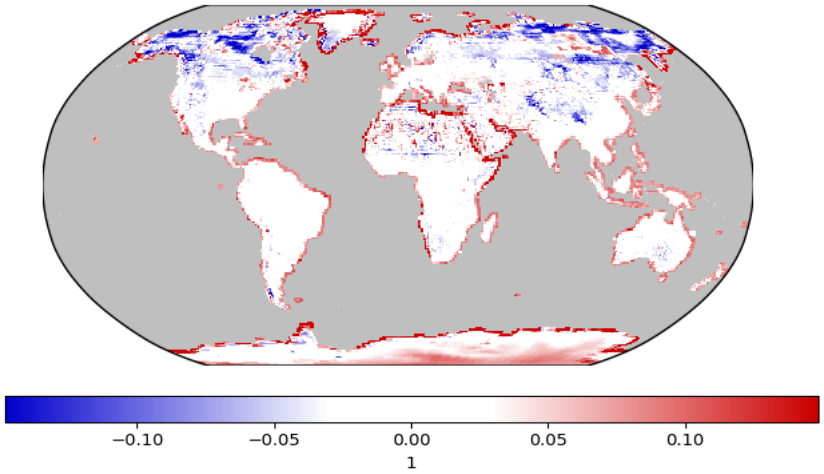


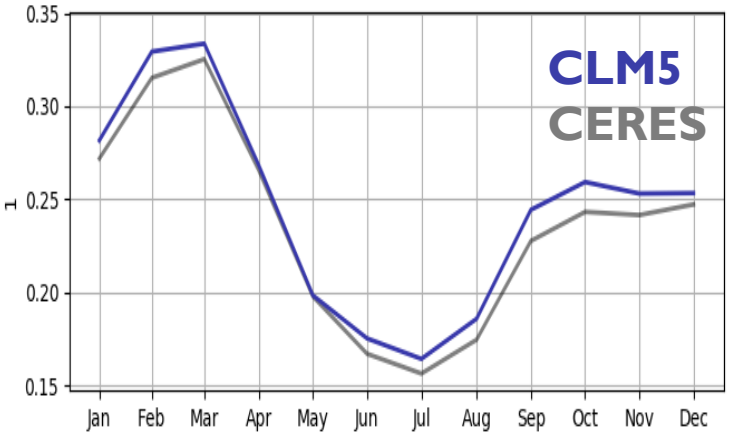
Flanner et al (2007), *JGR*
Flanner and Zender (2006), *JGR*
Flanner and Zender (2005), *GRL*



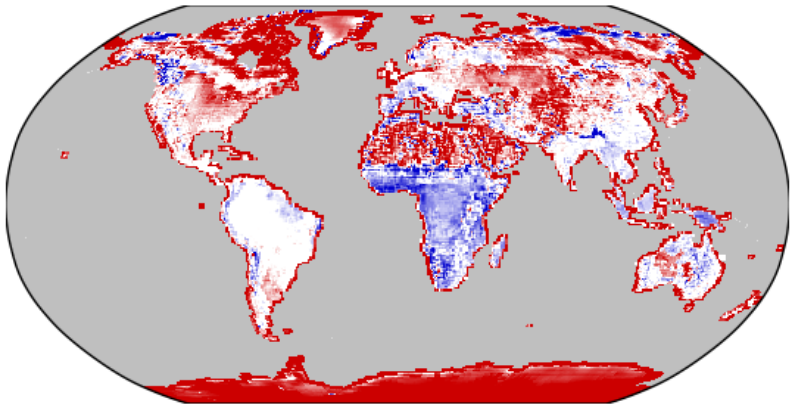
Biases in simulated land albedo

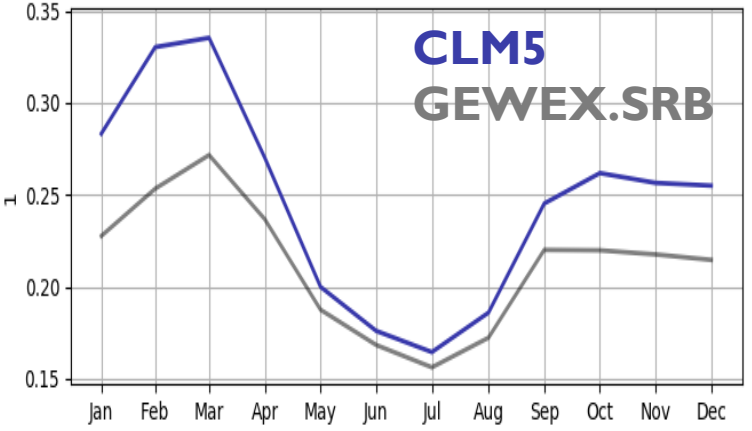
CLM5 – CERES: Ann mean





CLM5 - GEWEX.SRB: Ann mean






Snow-albedo feedback

1979–2008 change in CrRE: Seasonal cycle

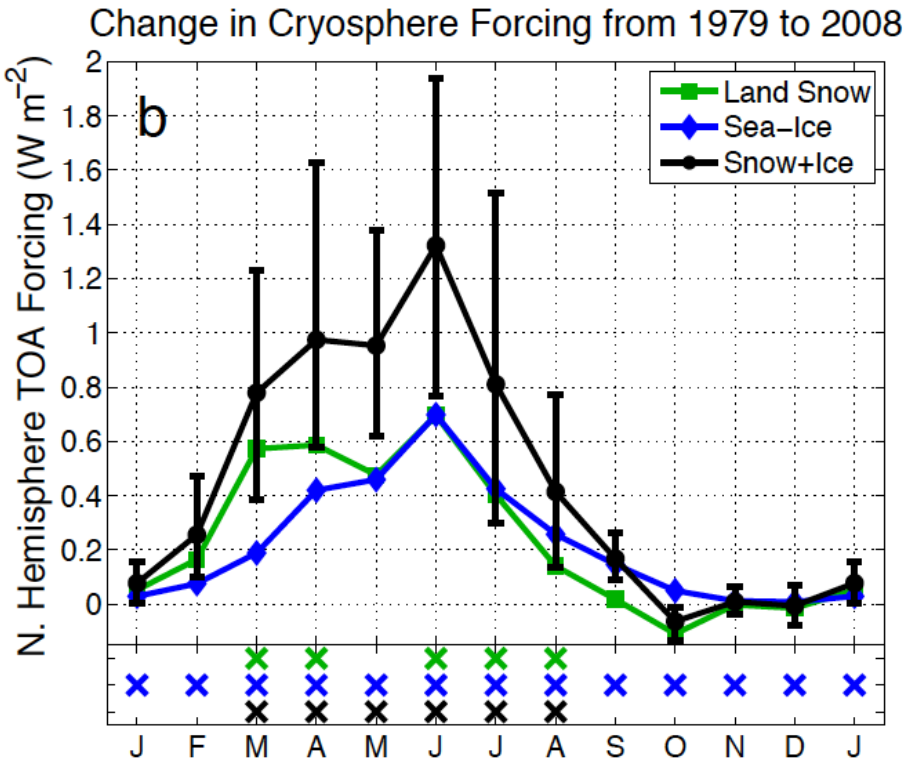
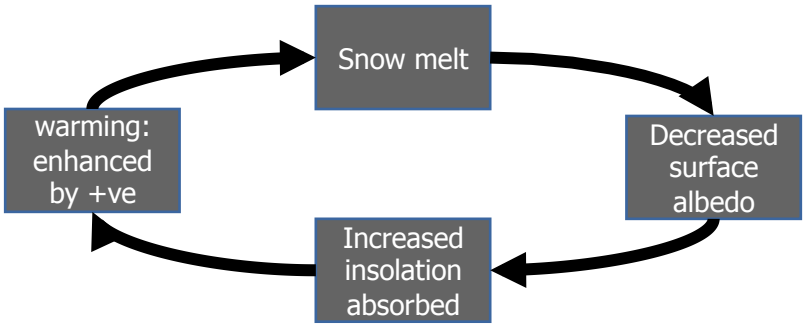


Figure : 'X' indicates month of statistically-significant change ($p = 0.01$)

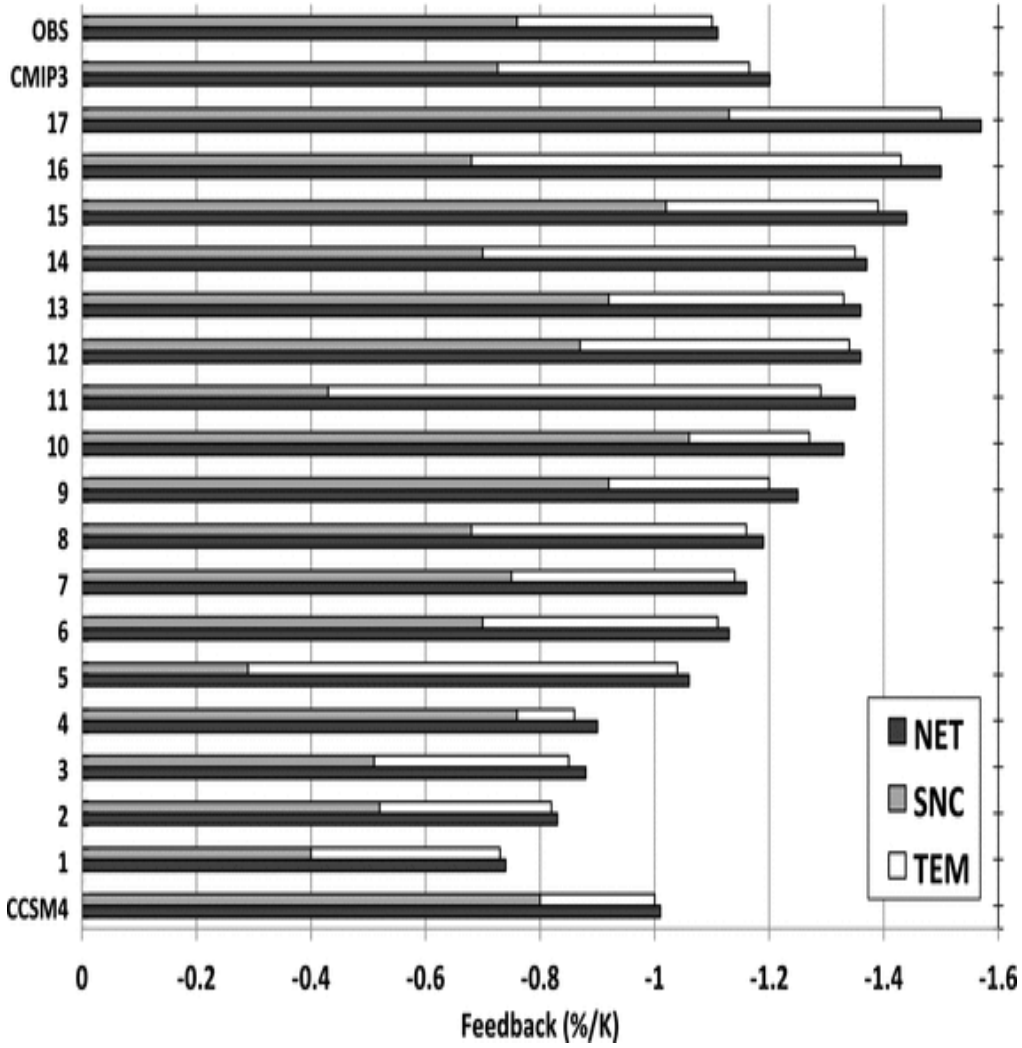
- Sea-ice peak change occurs in **summer**
- June peak in land snow change is sensitive to mountain snow cover estimates (Himalaya, Tien Shan)

Flanner et al., 2011

SNOW ALBEDO FEEDBACK (SAF)

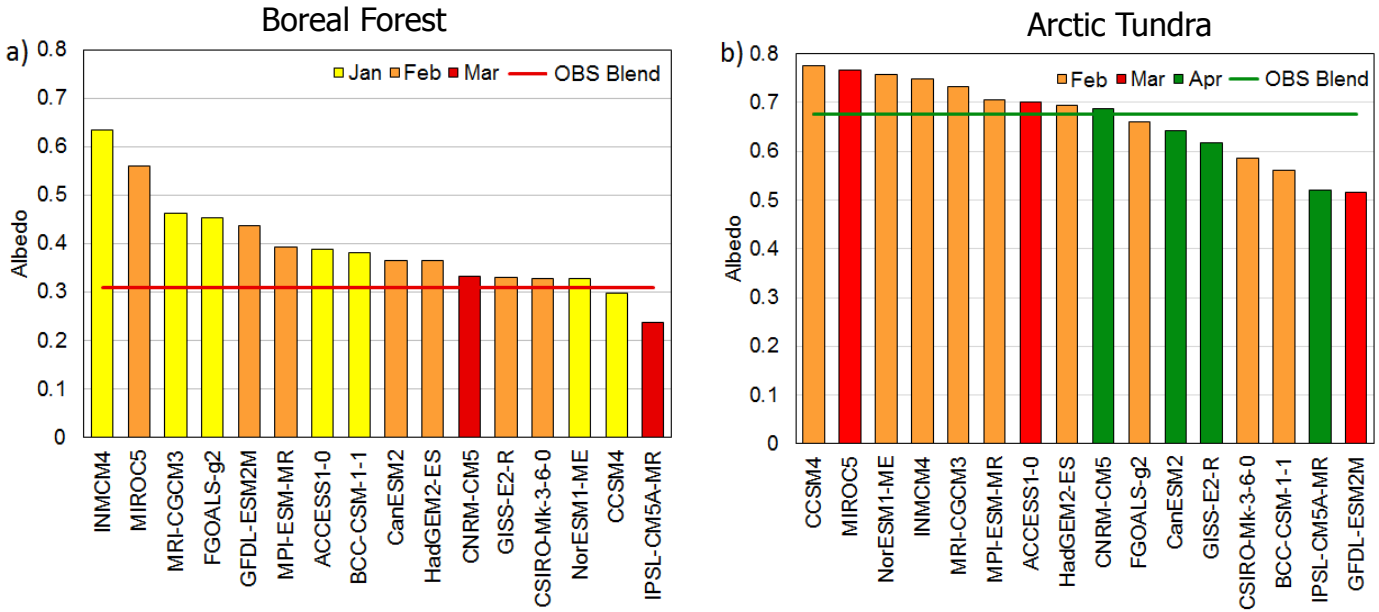


- SAF is a positive feedback climate mechanism and an important driver of regional climate change over the Northern Hemisphere (NH) extratropics.
- Models exhibit large variability in the strength of this process.
- Intermodel spread in SAF explains 40-50% of the variability in projected spring NH land warming.



Fletcher et al. 2012

LARGE BIASES IN SNOW-COVERED SURFACE ALBEDO

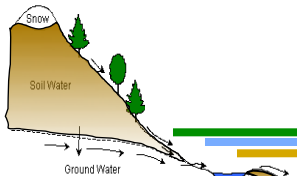


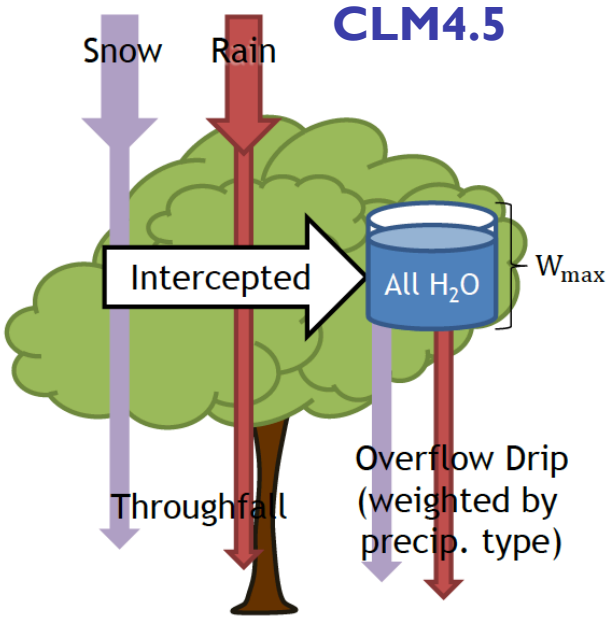
Maximum monthly mean climatological (1980-2005) surface albedo over the boreal forest and Arctic Tundra. Color coding shows when the peak albedo occurs.

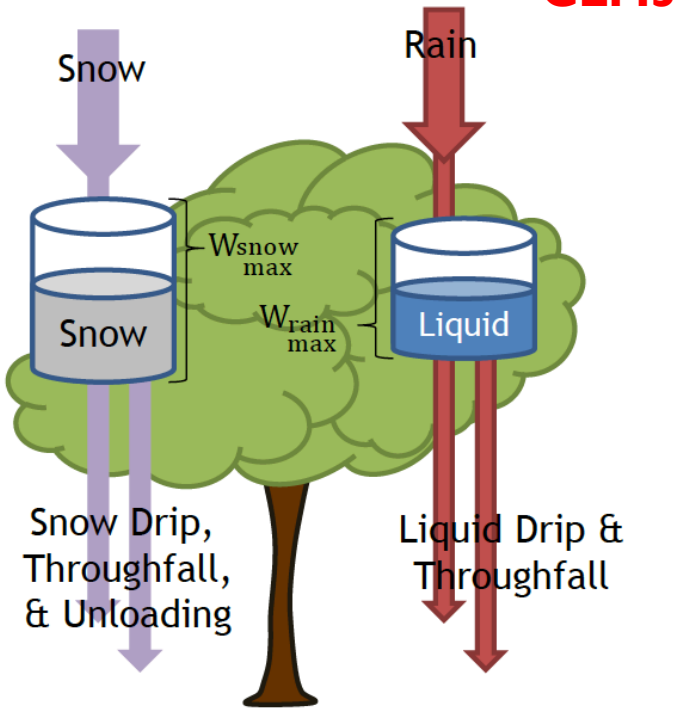
- Most climate models struggle to capture the **timing** and/or **magnitude** of seasonal changes in albedo over both boreal forest and Arctic tundra regions.
- For CCSM4, albedo decreases too early in winter because of an issue with how canopy snow is parameterized, leading to weak SAF.

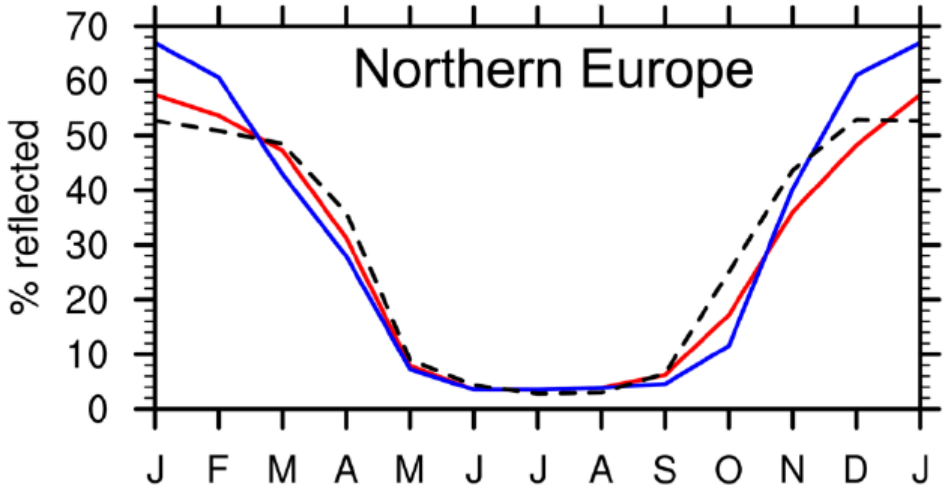
Thackeray et al., 2015

Snow-albedo feedback in CESM/CLM: Impact of canopy snow processes

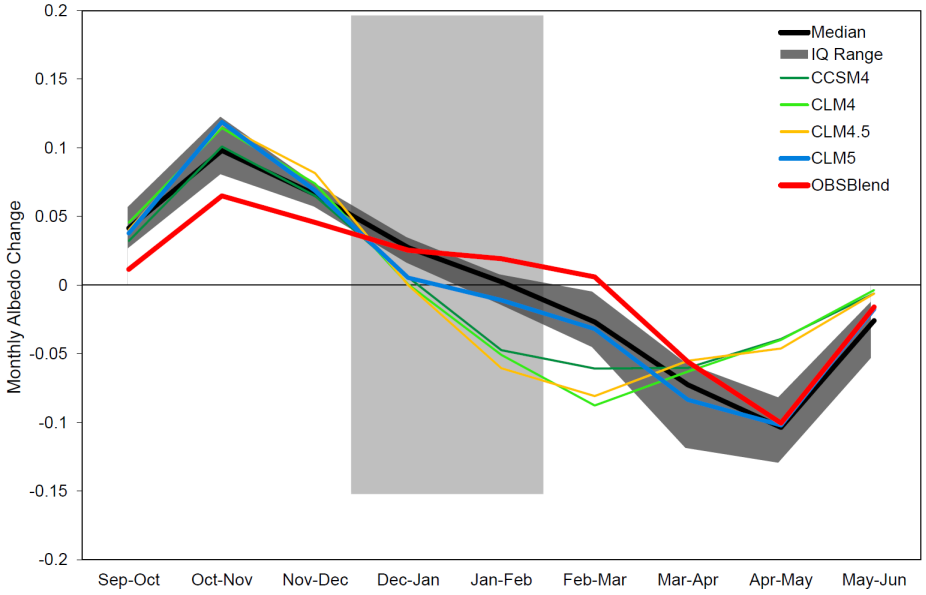








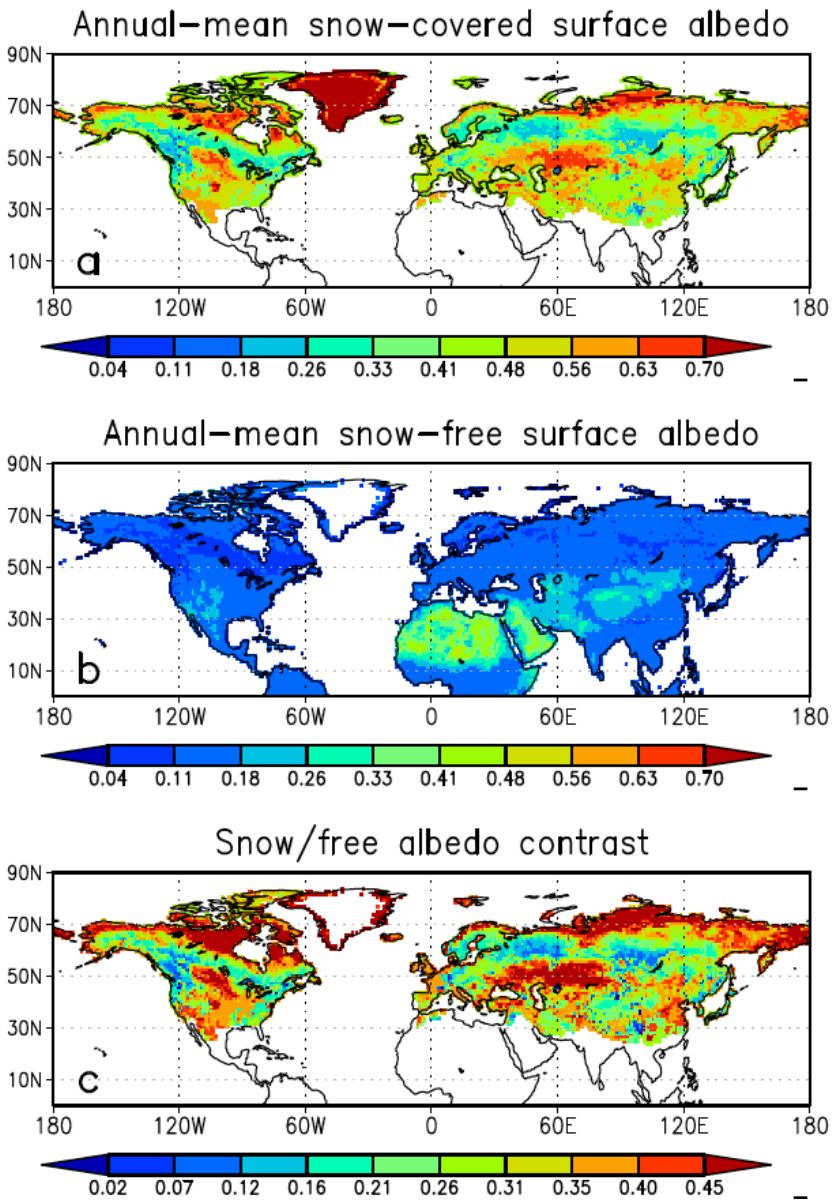
REDUCTION OF SAF BIAS IN CLM5



Model	Boreal Spring SAF (%/K)
CCSM4	-0.60
CLM4	-0.64
CLM4.5	-0.68
CLM5	-0.83
MODIS	-0.87

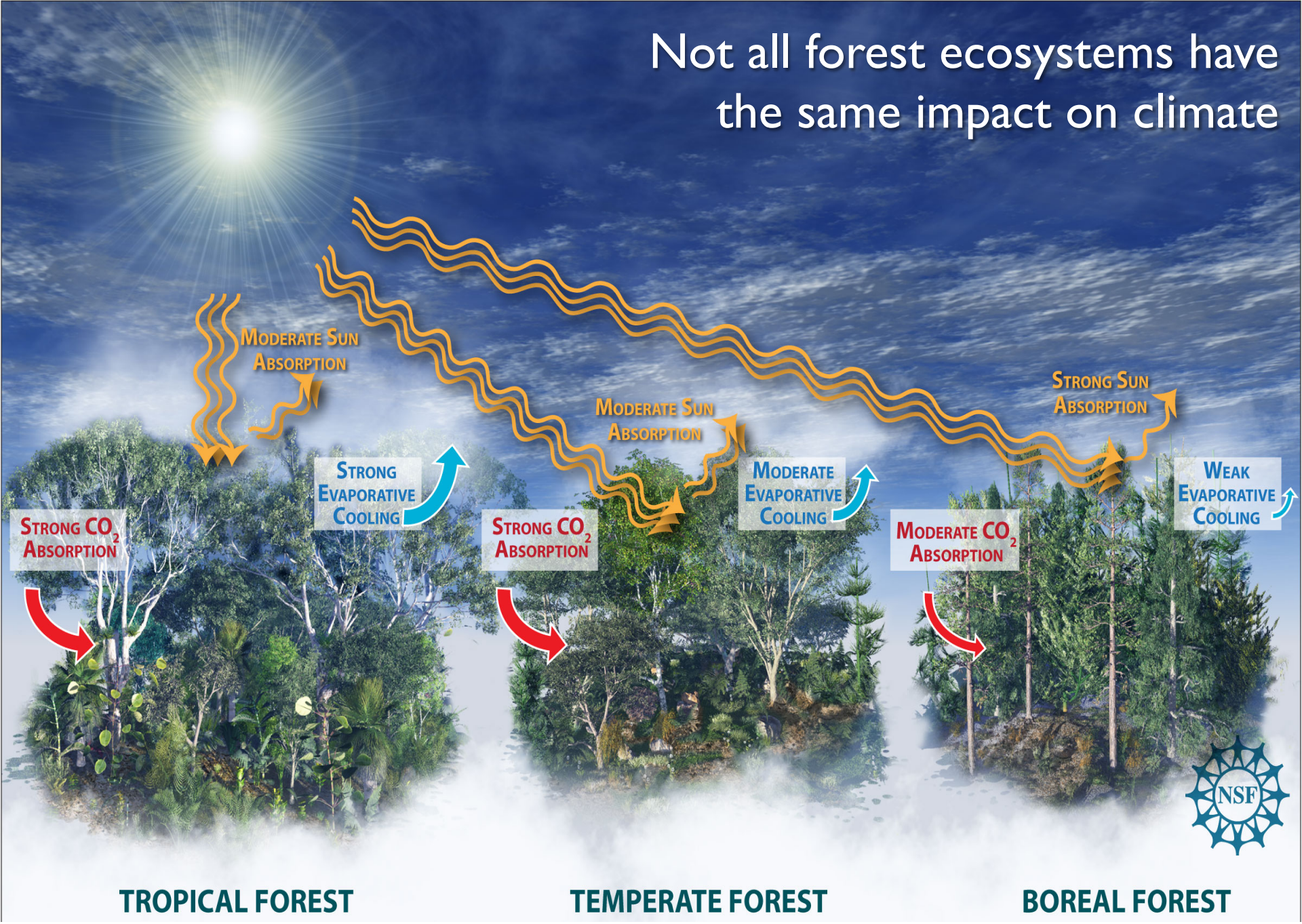
Monthly climatological change in albedo across the boreal forest (>75%) for the CMIP5 median, and several versions of CLM. The dark gray region captures the interquartile range for the CMIP5 ensemble. The light gray box shows when observational uncertainty is largest.

Snow-covered / snow-free albedo contrast ($\Delta\alpha_{\text{snow}}$)



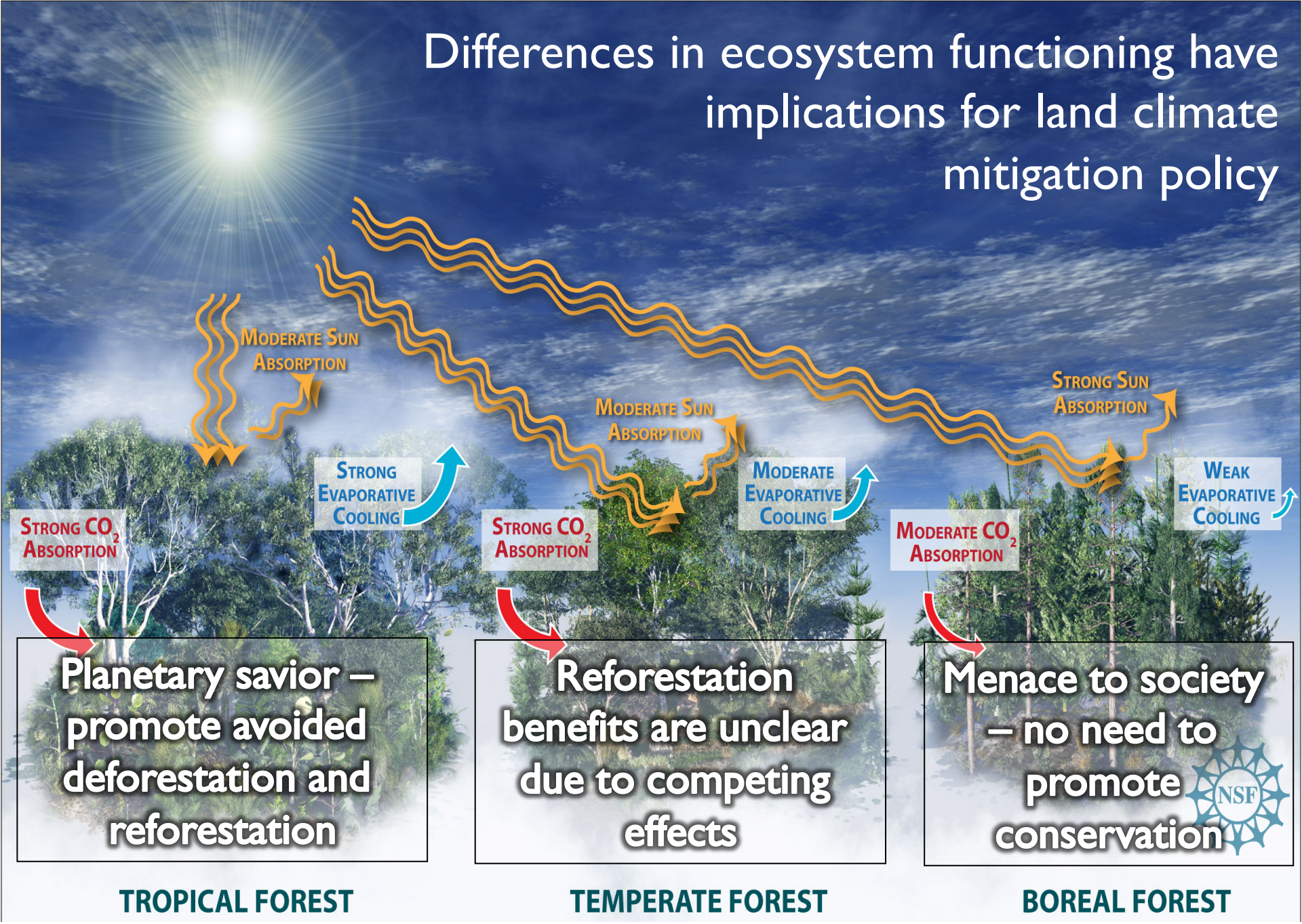
- Why is the contrast so variable in space?
- Reduced snow albedo impact over mature forests
- Large $\Delta\alpha_{\text{snow}}$ over grasslands and tundra
- Note that NOAA/Rutgers "snow-covered" surfaces can be up to 50% snow-free

Image: Frans Lanting/Robert Harding Picture Library



Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*



Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

Land surface heterogeneity
CLM subgrid tiling structure

Gridcell

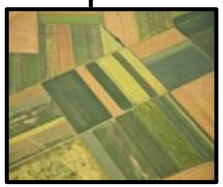
Landunit

Vegetated

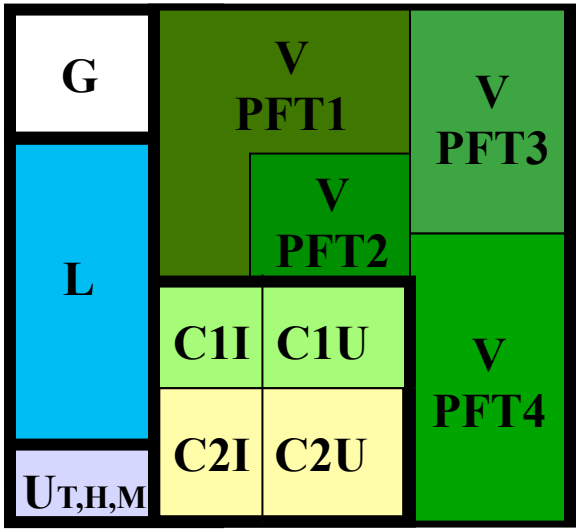
Lake

Urban

Glacier



Crop



Column

Soil

Unirrig

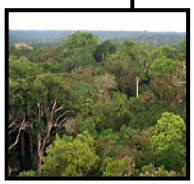
Irrig

Unirrig

Irrig

PFT

PFT1



PFT2

PFT3

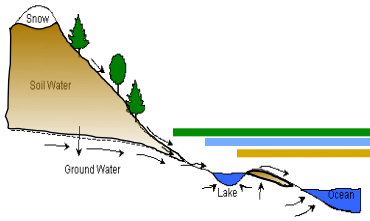
PFT4 …

Crop1

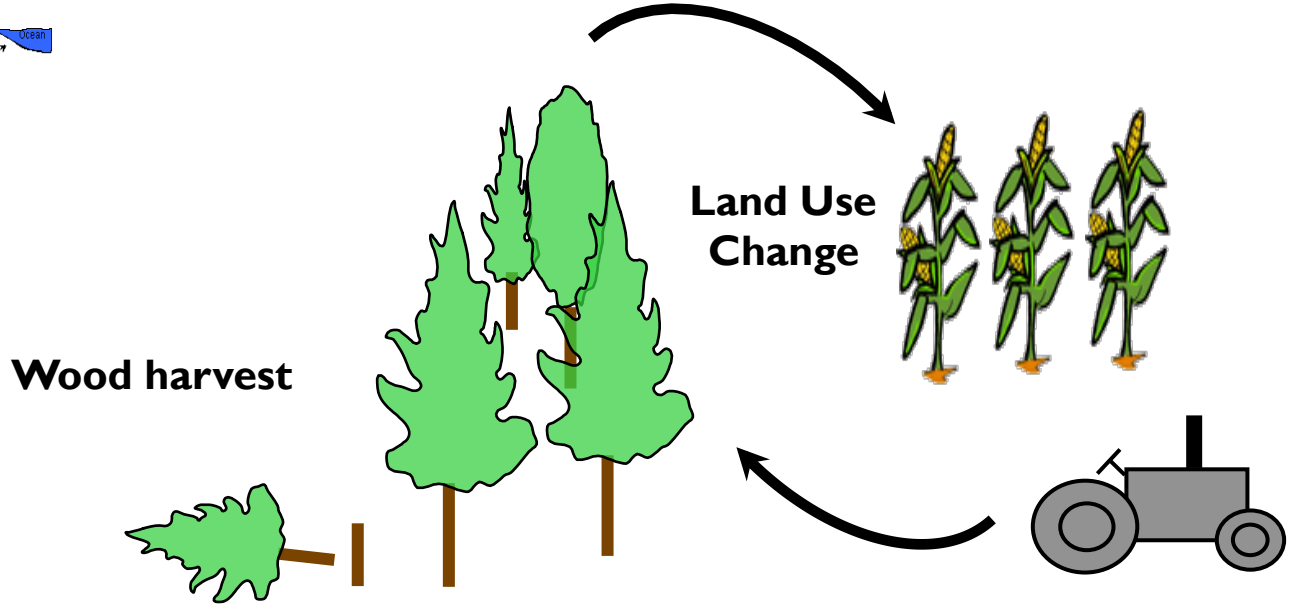
Crop1

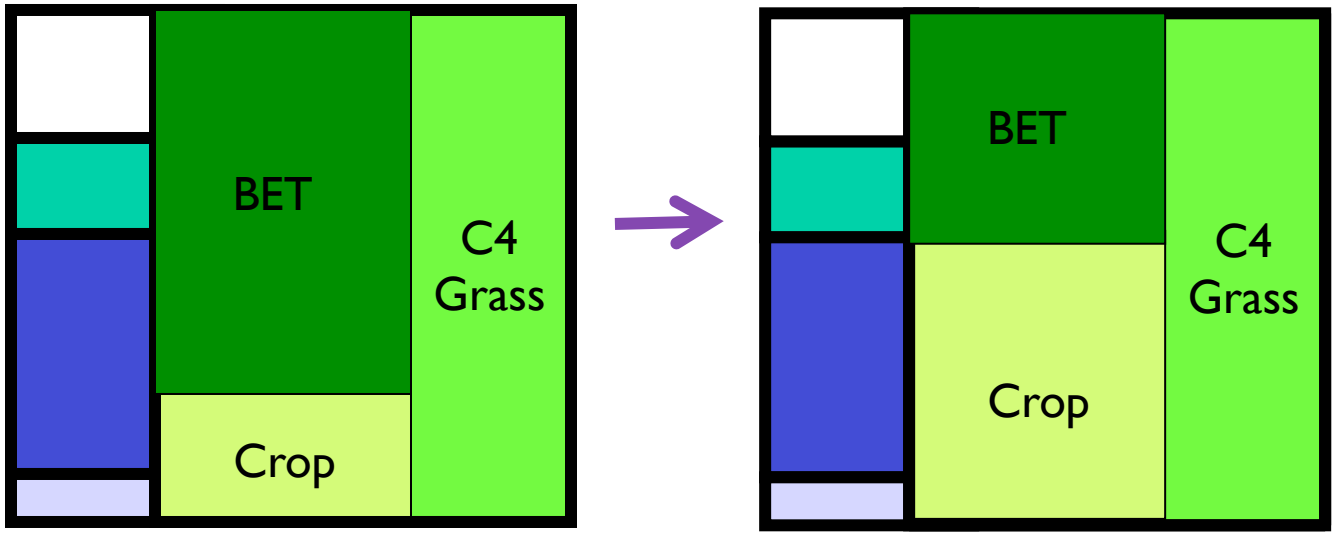
Crop2

Crop2 …



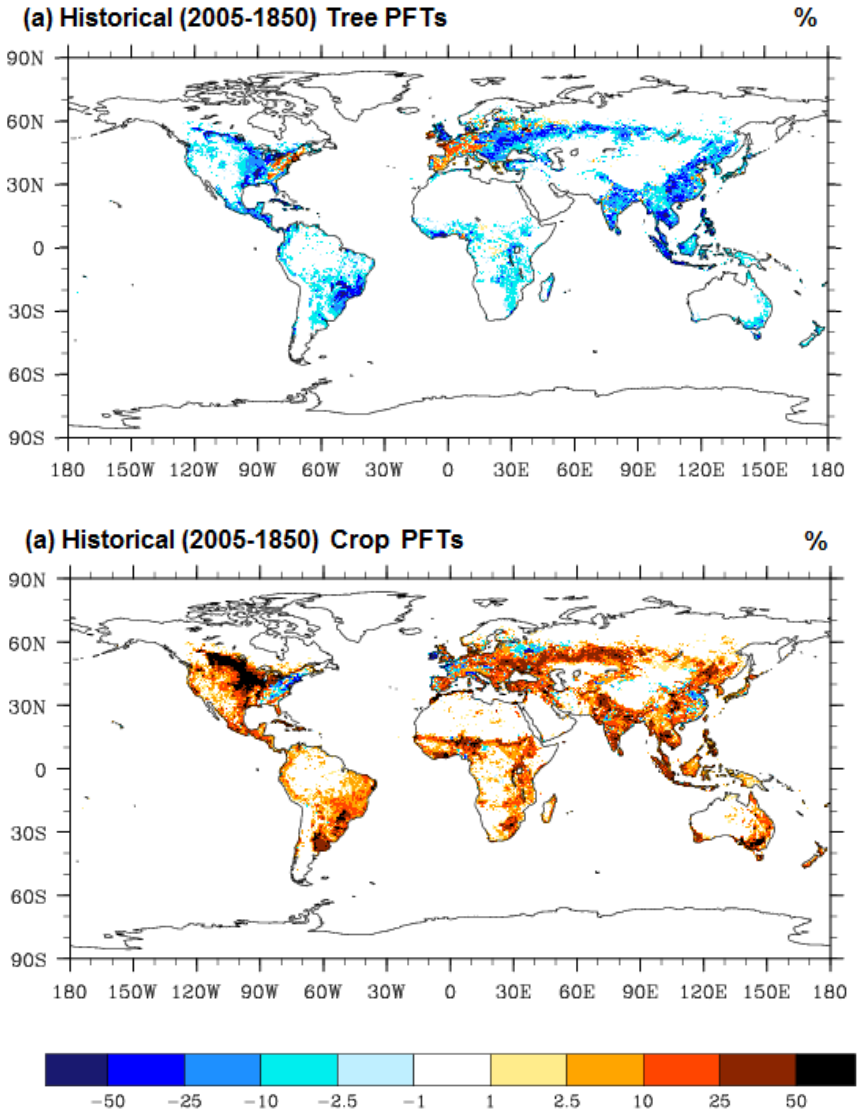
Land-cover / land-use change (prescribed)





Historical land use & land cover change, 1850-2005

Change in tree and crop cover (% of grid cell)



Historical LULCC

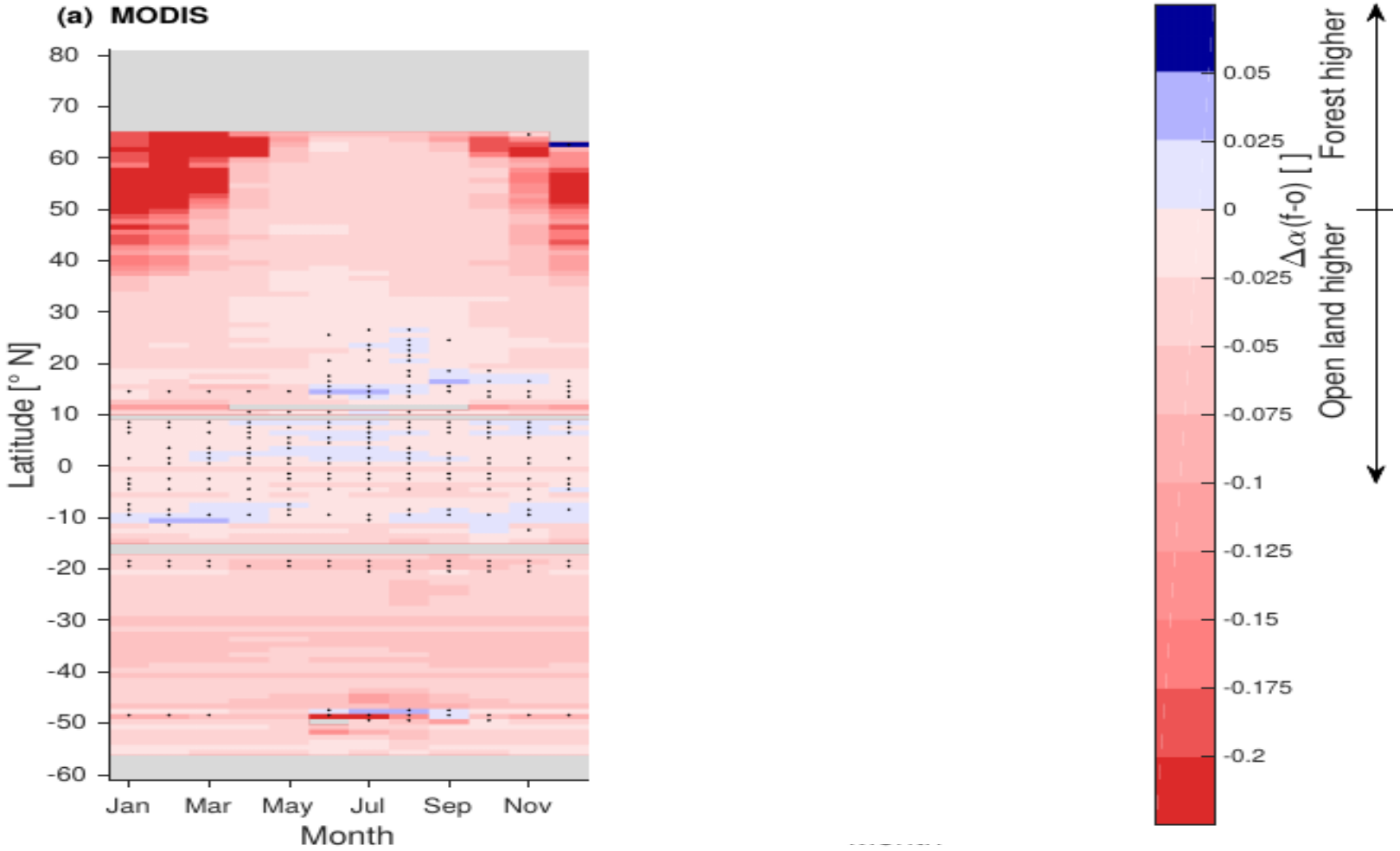
- ❑ Loss of tree cover and increase in cropland
- ❑ Farm abandonment and reforestation in eastern U.S. and Europe
- ❑ Extensive wood harvest

Impact of LULCC on climate through

- Albedo
- Surface roughness
- Surface heat flux partitioning
- Carbon exchange

P. Lawrence et al. (2012) J Climate 25:3071-3095

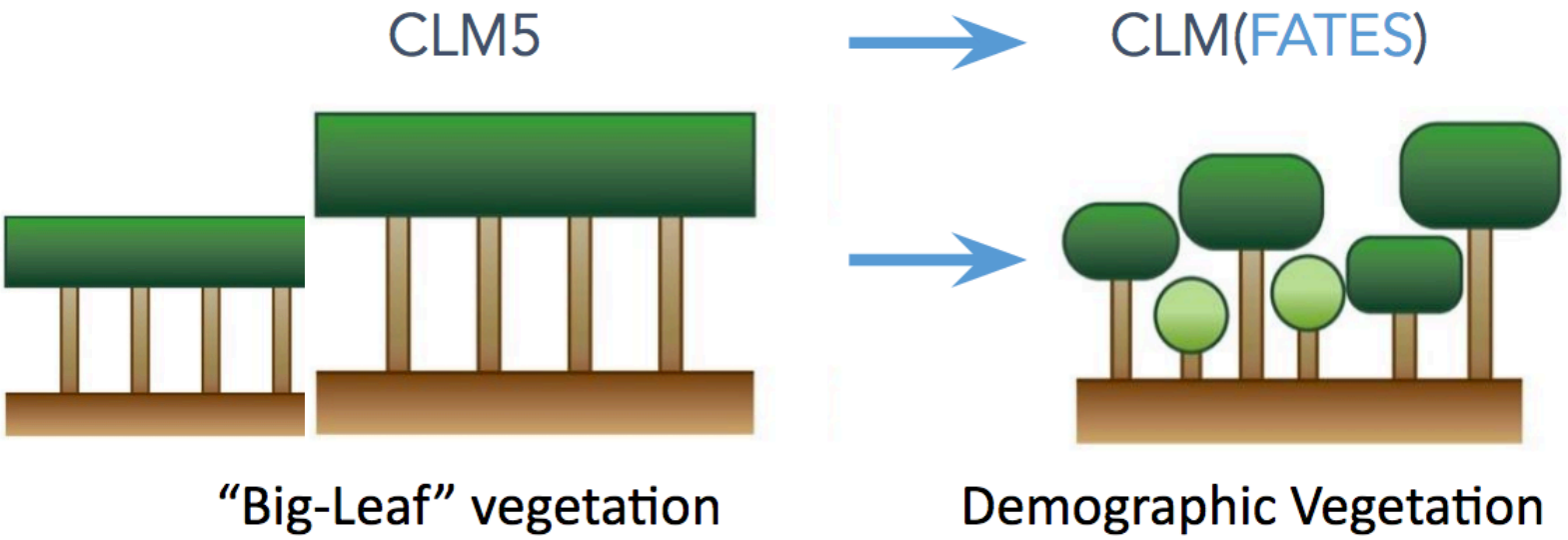
Albedo



Meier et al. (submitted)

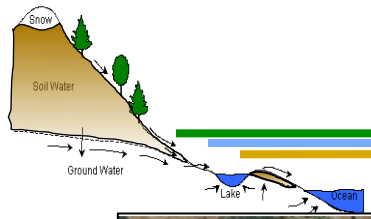
Development efforts related to radiation

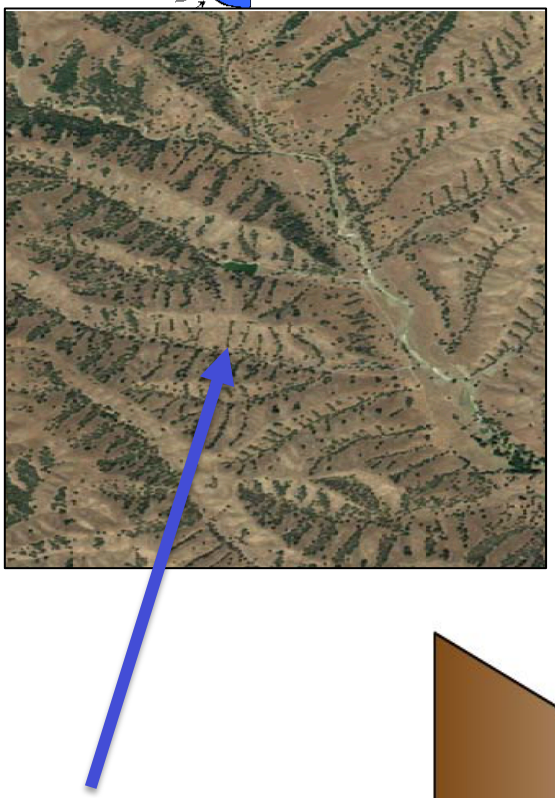
Plant competition for light

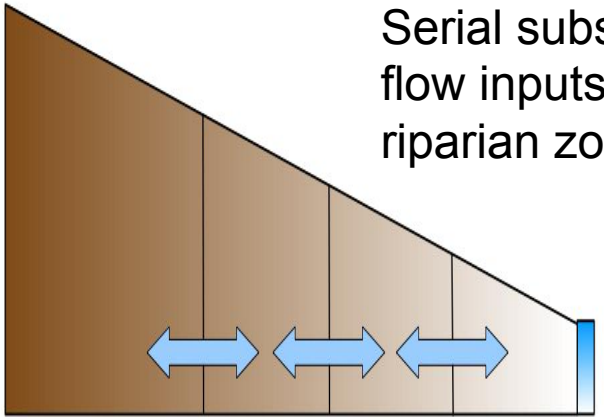


Natural vegetation patterns imply subgrid controls from soil moisture convergence, slope, and aspect

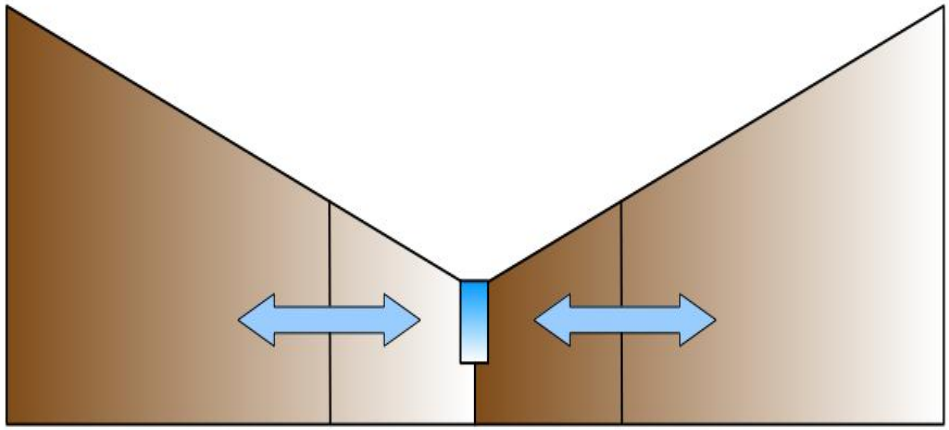
Representative hillslopes (CLM5 option)





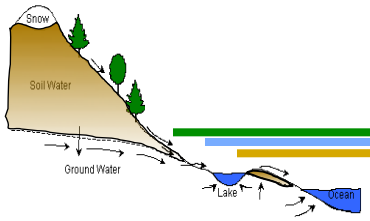


Serial subsurface flow inputs to riparian zone



Independent (parallel) subsurface flow inputs to riparian zone

Swenson et al., in prep



Soil Temperature (1m)

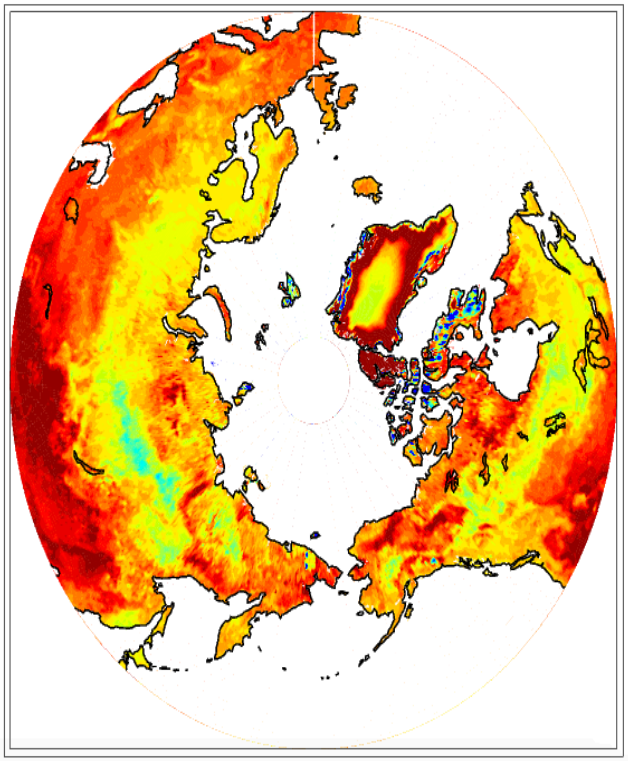
South facing

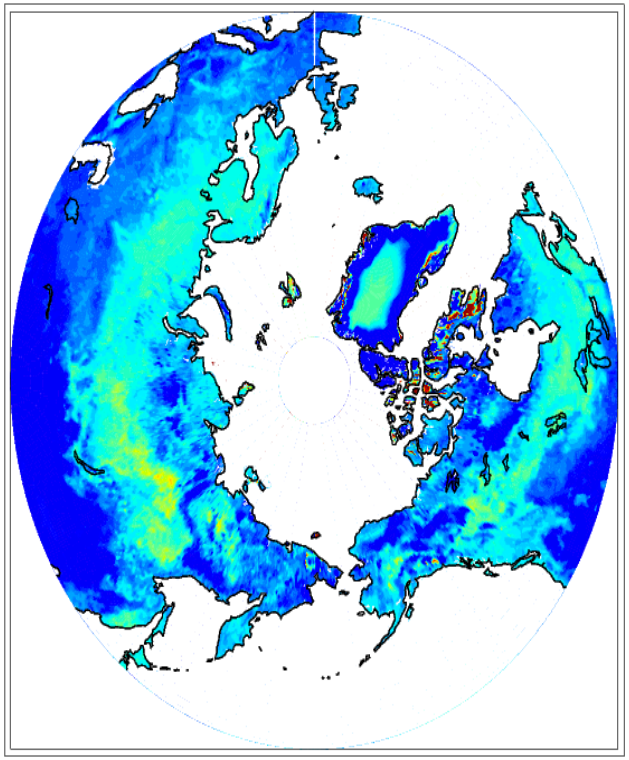
North facing

+2°C

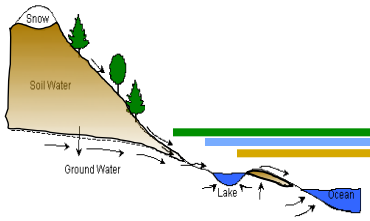
0°C

-2°C



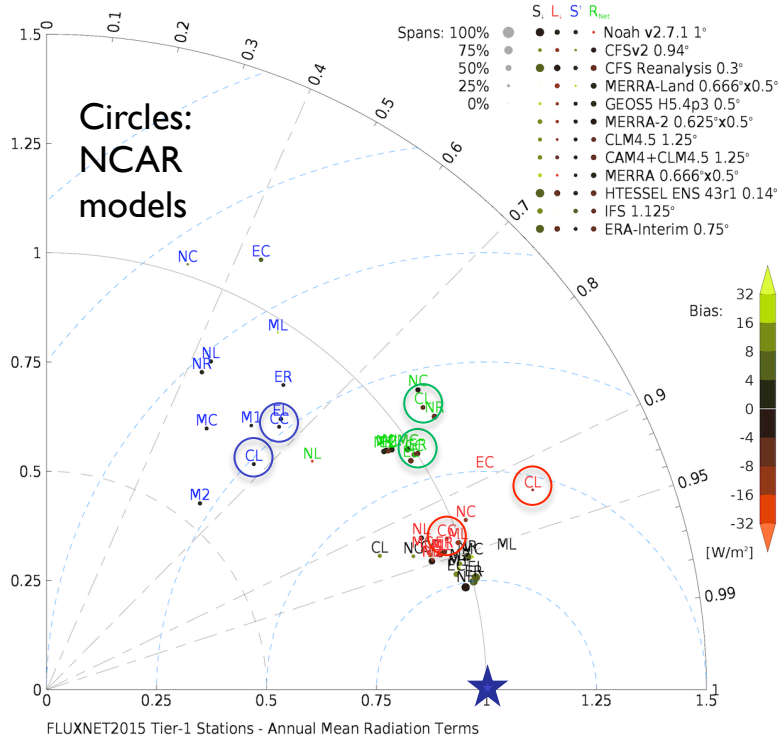


Questions



Land surface energy budget terms

- Compared across ~160 FLUXNET sites, LSMs, GCMs and reanalyses struggle to reproduce even the global pattern of annual means.

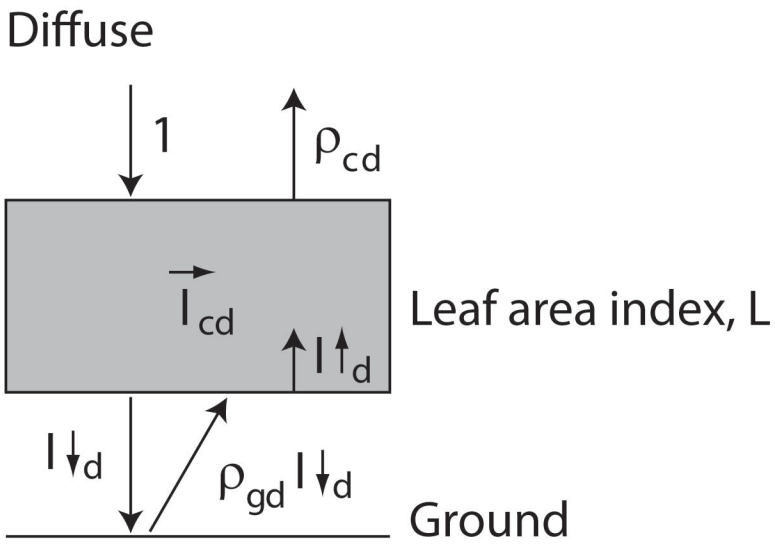


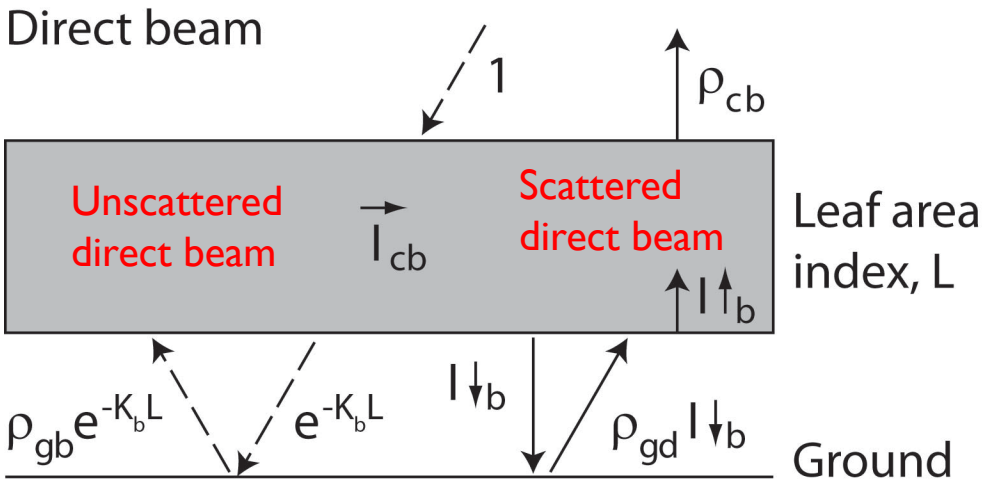
SW Down
LW down
SW Up
R_{Net}

- There appears to be a real problem with LSM surface albedos (blue) – is this a site-grid scaling problem or more serious?
- Basic radiation errors impair simulation of surface sensible and latent heat fluxes, and thus L-A feedbacks.

Dirmeyer *et al.* (2018; JHM)

Two-stream radiative transfer

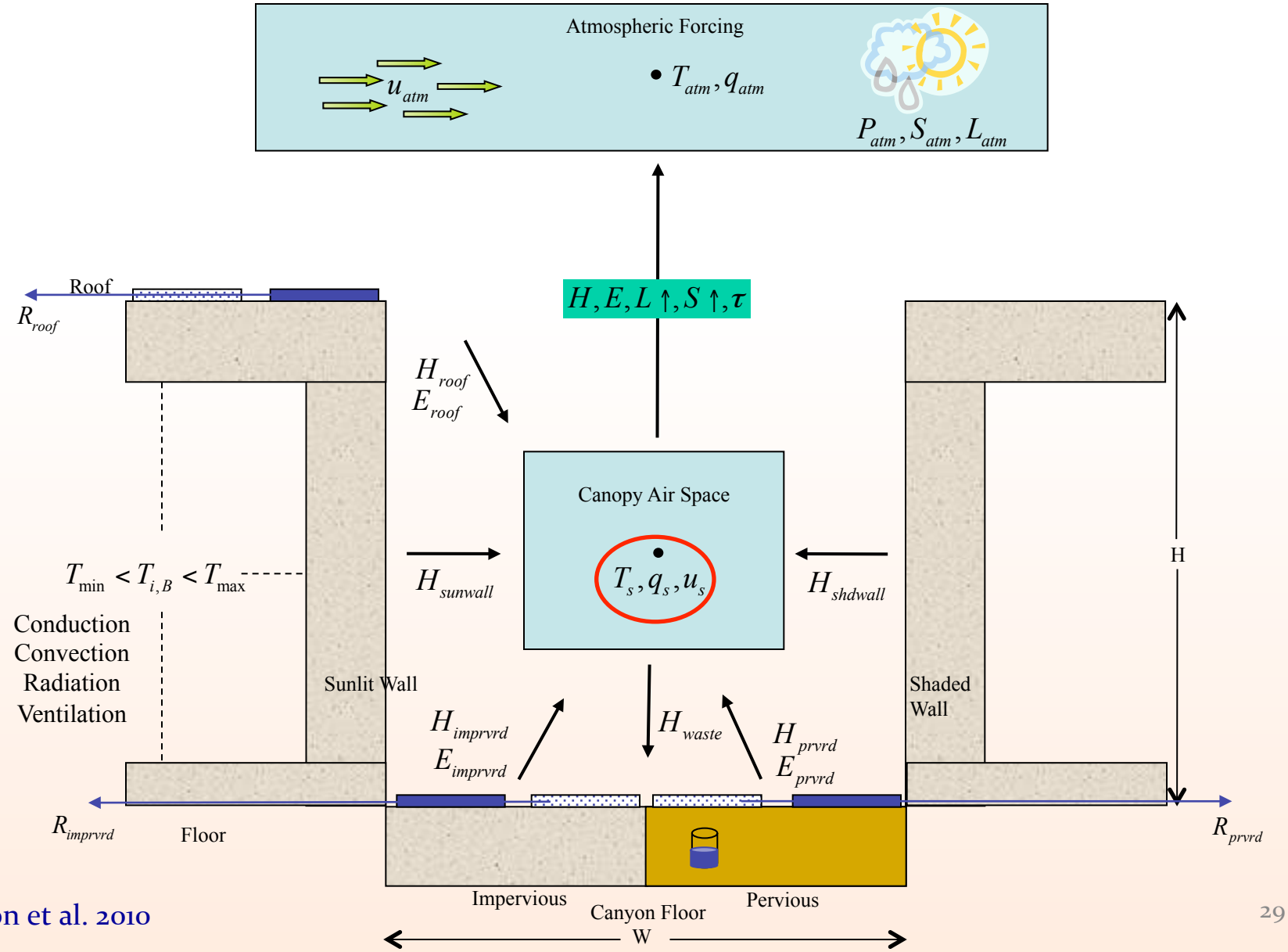




Radiative transfer uses the two-stream approximation (Dickinson, Sellers) to determine reflected and absorbed solar radiation

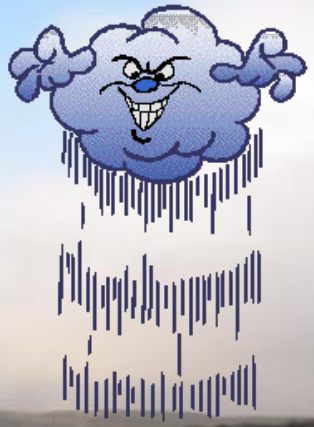
Slide courtesy G. Bonan

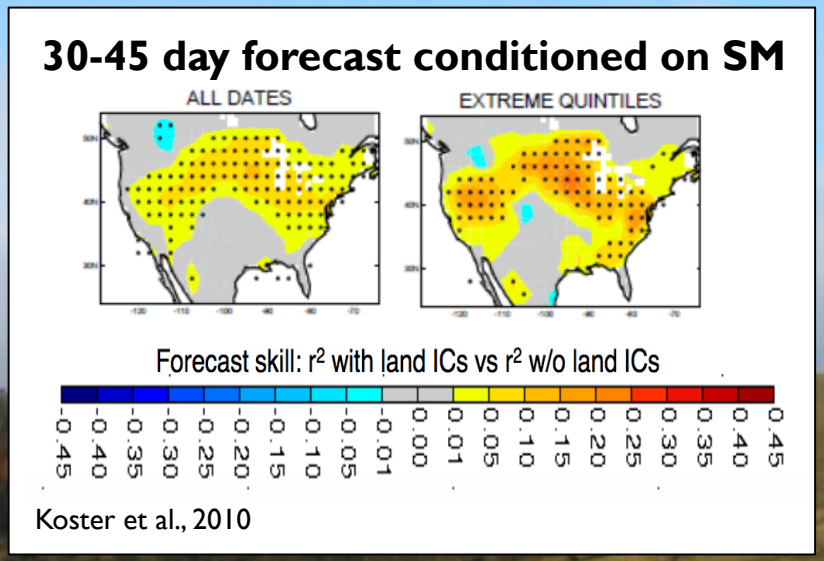
Urban Model



Oleson et al. 2010

Land modelling, why? Land-atmosphere interactions

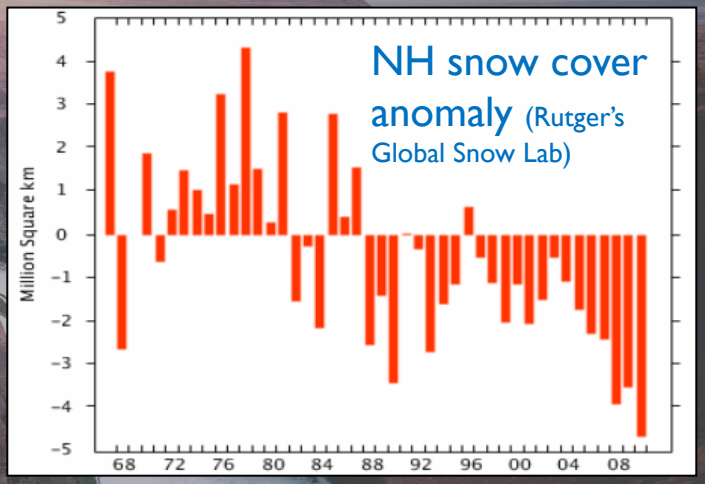




- When, where, and by how much do land fluxes influence atmosphere, surface temperature, clouds, precipitation, etc.?
- Land-driven predictability
  - Significant skill, especially when conditioned on amplitude of initial soil moisture anomaly
  - Increased land-atmosphere coupling in future warmer climate, increased land-driven skill?
- Land influence on extremes

Land modeling, why? Water

- Land feedbacks on droughts and floods
- Snow-albedo and snow-soil T feedbacks
- Water and food security
  - >1/6th world population dependent on water from seasonal snowpacks
- Water – plant interactions
  - Plant water use efficiency likely to increase with CO_2
- Streamflow prediction



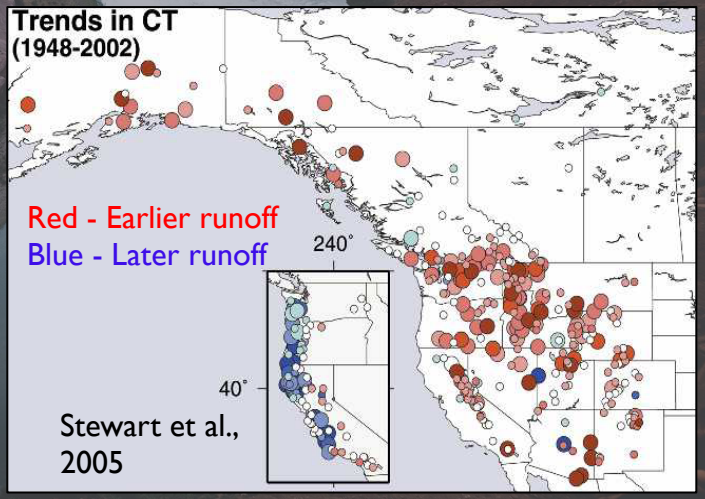
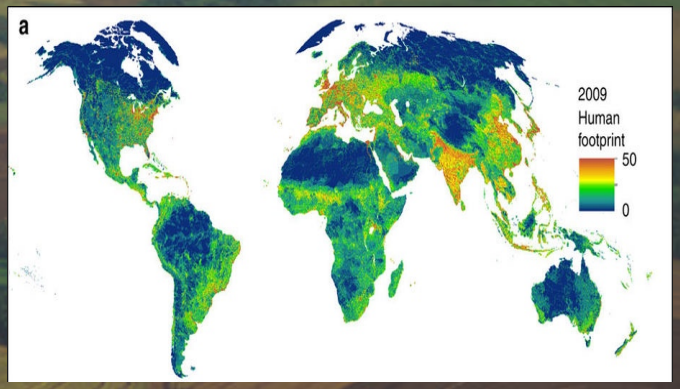
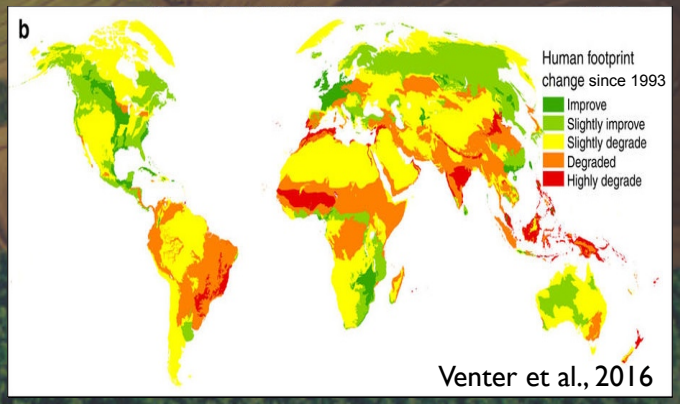


Image: Kimon Maritz

Land modeling why? Land-use and land-cover change

- ~25% non-ice land area undergone anthropogenic land-cover change
- ~80% non-ice land area under some form of land management
- Regionally, LULCC as impactful on surface climate as greenhouse gases
- ~1/3 of direct historic carbon emissions (180 ± 80PgC from land use, ~400 PgC from fossil fuel and cement),
- Deforestation: loss of Additional Sink Capacity yields indirect C impact
- Effectiveness of afforestation and biofuels for CO_2 mitigation
- Urban-rural differences in climate change impacts, e.g. ,heat stress





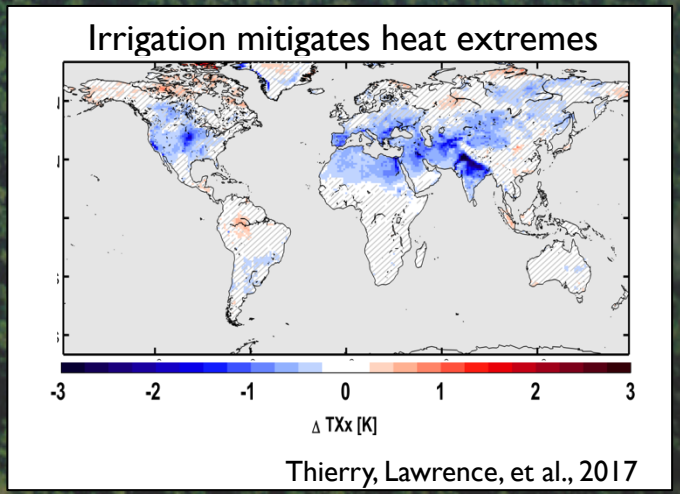


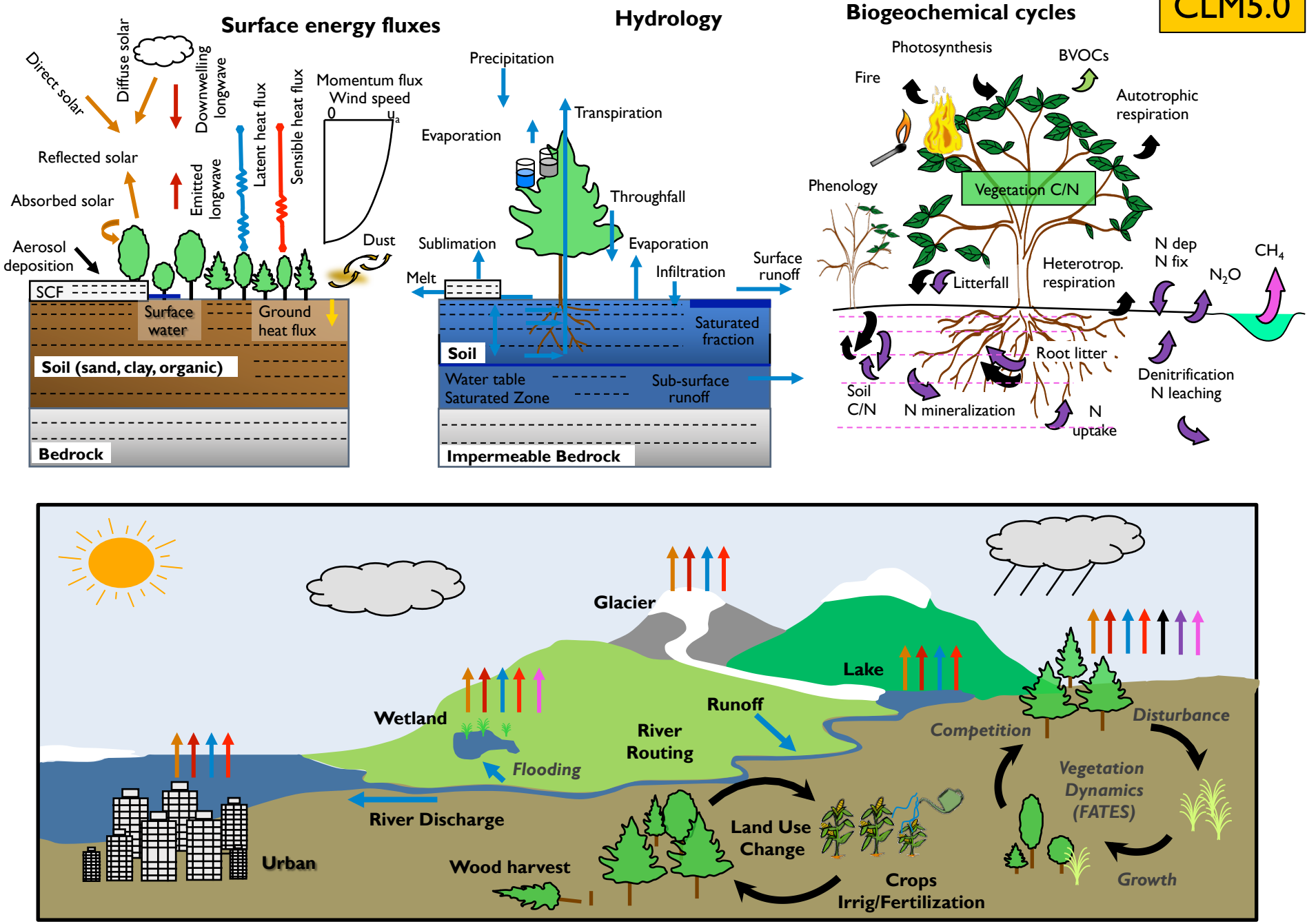
Image: Frans Lanting/Robert Harding Picture Library

Land modeling, why? Carbon and ecology

- Carbon and nitrogen cycle interactions and their impact on long term trajectory of terrestrial carbon sink
- High uncertainty in projected land C sink
  - Emissions driven RCP8.5: 795 to 1140 ppm (source of ±1.2C uncertainty on top of 3.7C projected change)
- Vulnerability of ecosystems to climate change as well as natural and human disturbances
- Ecosystem services
- Ecosystem management to mitigate climate change

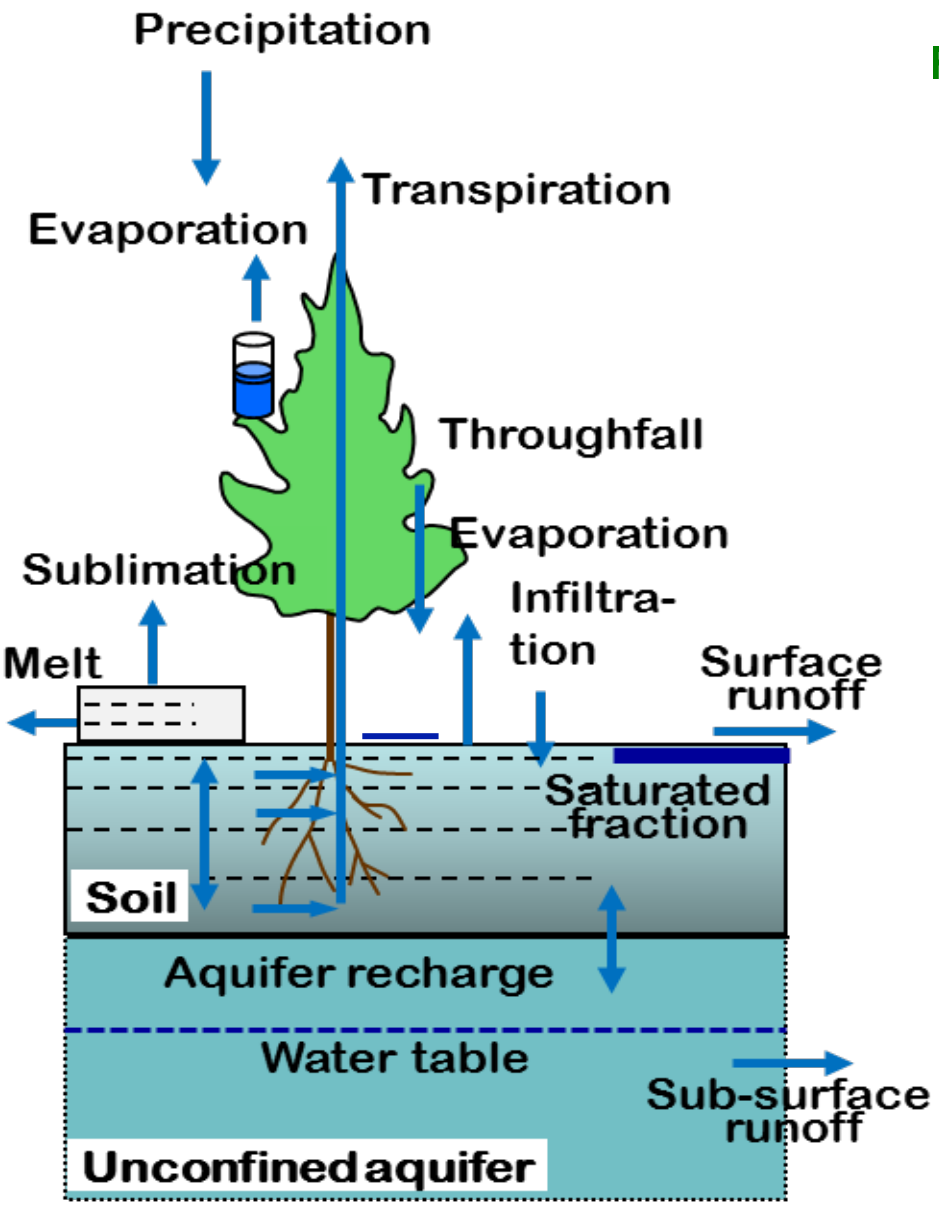
Image: Joel Vodell

CLM5.0



Lawrence et al., 2011; Lawrence et al., 2018

… and the Surface Water Balance



$$P = E_S + E_T + E_C + R + (\Delta W_{soi} + \Delta W_{snw} + \Delta W_{sfcw} + \Delta W_{can}) / \Delta t$$

P is rainfall/snowfall,

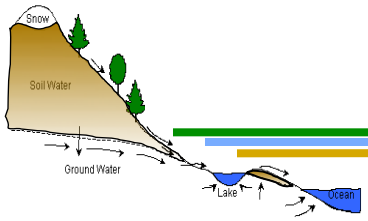
E_S is soil evaporation,

E_T is transpiration,

E_C is canopy evaporation,

R is runoff (surf + sub-surface),

$\Delta W_{soi} / \Delta t$, $\Delta W_{snw} / \Delta t$, $\Delta W_{sfcw} / \Delta t$, $\Delta W_{can} / \Delta t$, are the changes in soil moisture, surface water, snow, and canopy water over a timestep

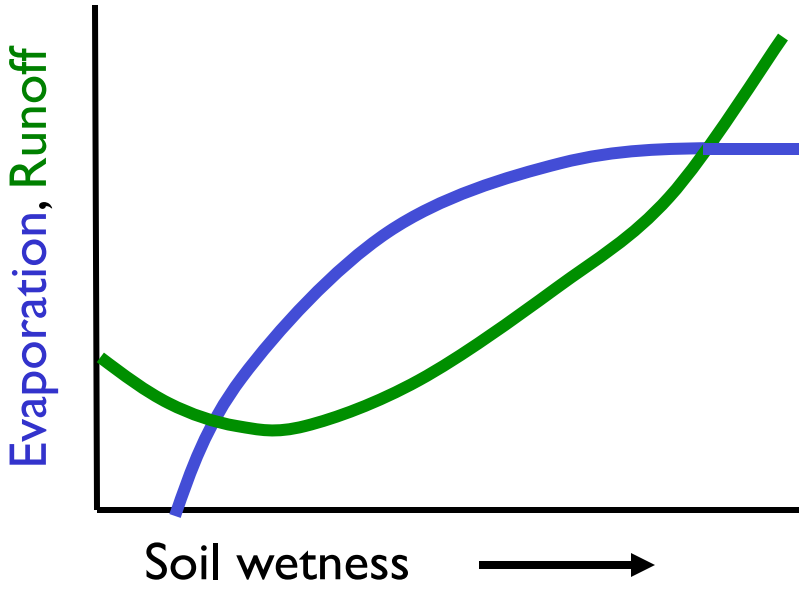


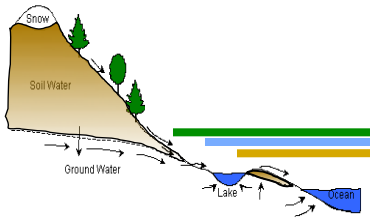
Terrestrial water and energy cycles intricately linked

"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related through soil moisture."

(Koster and Milly, 1997).

Runoff and evaporation both vary non-linearly with soil moisture

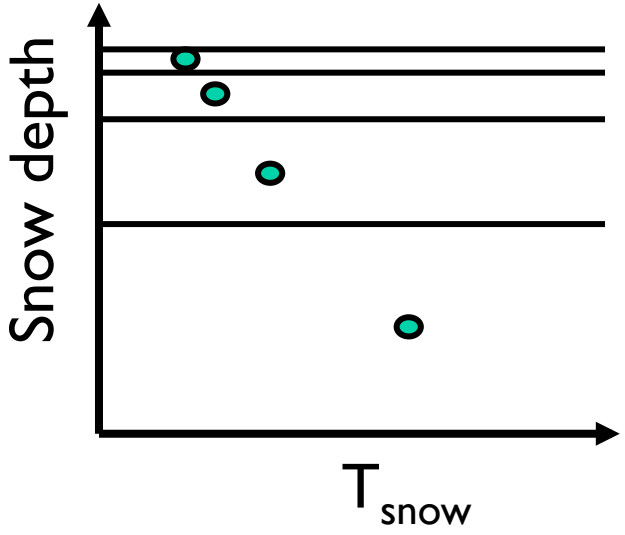




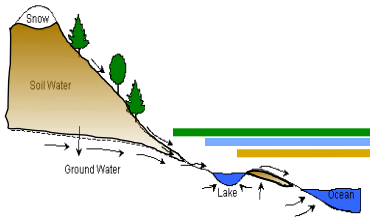
Land model complexity: Snow model example

State Variables

$$N, w_{liq,i}, w_{ice,i}, \Delta z_i, T_i$$



- Up to 10-layers of varying thickness
- Represented processes
  - Accumulation and fresh snow density *f* (T, wind)
  - Snow melt and refreezing
  - Snow aging
  - Water and energy transfer across snow layers
  - Snow compaction
    - destructive metamorphism due to temperature and wind
    - overburden
    - melt-freeze cycles
  - Sublimation
  - Aerosol (black carbon, dust) deposition
  - Canopy snow storage and unloading
  - Canopy snow radiation
  - Snow burial of vegetation
  - Snow cover fraction
- Missing processes
  - Blowing snow
  - Subgrid variations in snow depths
  - Depth hoar

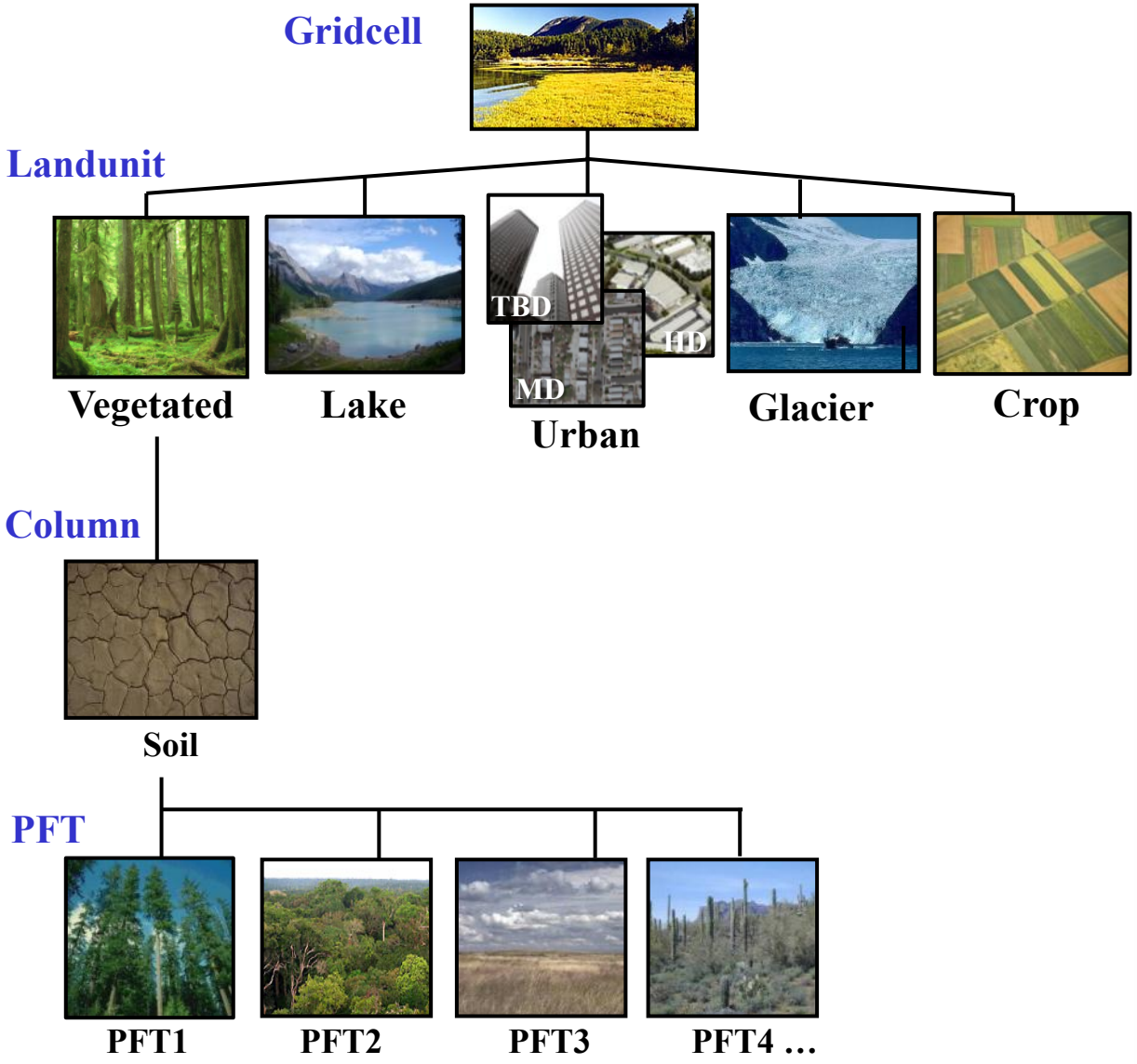


Plant Functional Type Parameters

- Optical properties (visible and near-infrared):
  - Leaf angle
  - Leaf reflectance
  - Stem reflectance
  - Leaf transmittance
  - Stem transmittance
- Fire:
  - Combustion completeness
  - Fire mortality
- Land models are parameter heavy!!!

- Morphological properties:
  - Leaf area index (annual cycle)
  - Stem area index (annual cycle)
  - Leaf dimension, leaf orientation
  - Roughness length/displacement height
  - Canopy top and bottom height
  - Root depth and distribution
- Photosynthetic parameters:
  - Specific leaf area
  - m (slope of conductance-photosynthesis relationship)
  - Vcmax (maximum rate of carboxylation)
  - Leaf carbon to nitrogen ratio
  - Fraction of leaf nitrogen in Rubisco
  - Root conductivity, plant conductivity

Land surface heterogeneity
CLM subgrid tiling structure



Plant Functional Types:

0. Bare

Tree:

1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous / Understorey:

9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. C3 Arctic Grass
13. C3 non-Arctic Grass
14. C4 Grass
15. Crop